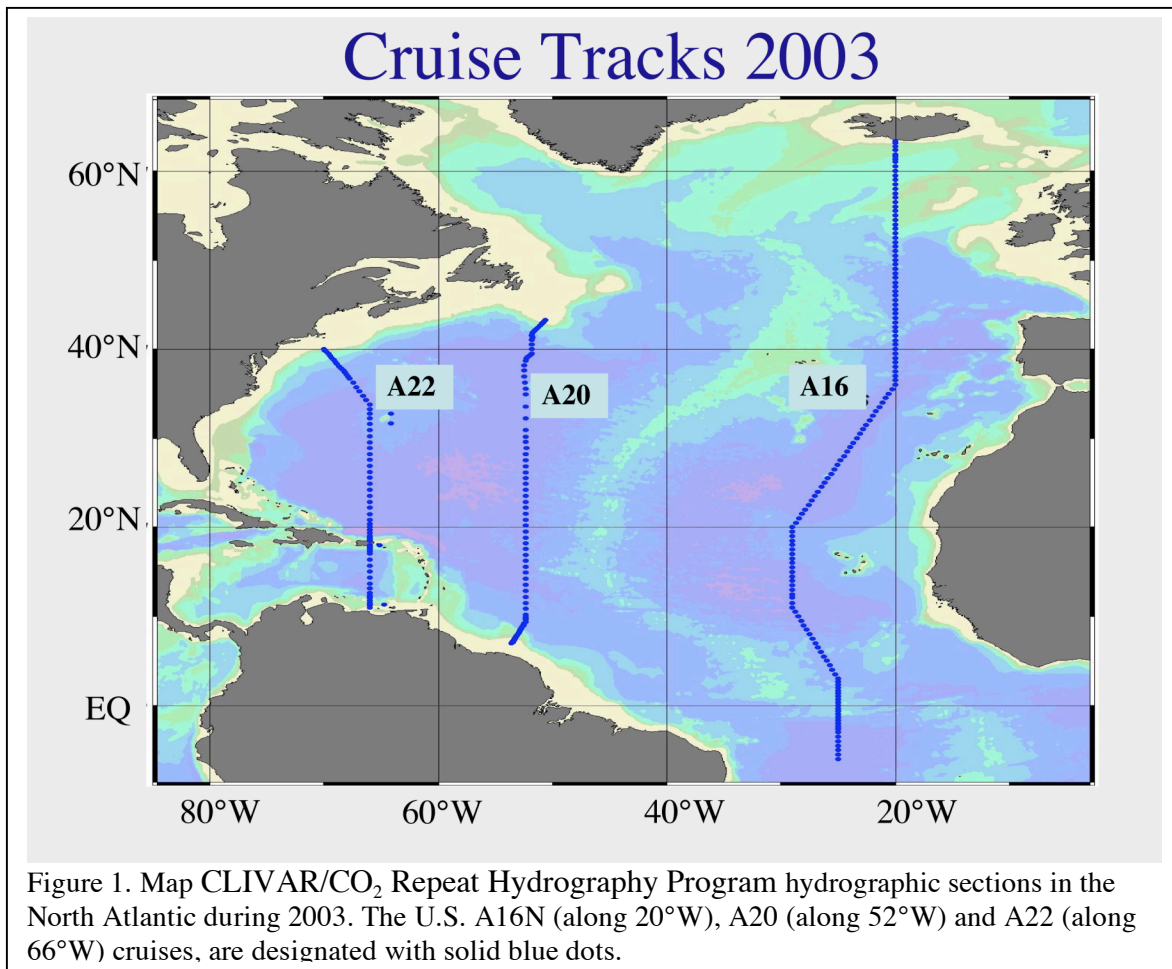


Repeat Hydrography Cruises Reveal Chemical Changes in the North Atlantic

Three North Atlantic cruises in 2003 marked the beginning of the U.S. Contribution to a large international effort to document long-term trends in carbon storage and transport in the global oceans by reoccupying selected hydrographic sections on decadal time-scales. Early results from this work showed significant long-term changes in oxygen and carbon dioxide and several other measurable parameters since the last global survey in the 1990s.

The ocean has a memory of the climate system and is second only to the sun in effecting variability in the seasons and long-term climate change. It is estimated that the ocean stores 1000 times more heat than the atmosphere, and 50 times more carbon. Additionally, the key to possible abrupt climate change may lie in deep ocean circulation. Accordingly, the U.S. CLIVAR/CO₂ Repeat Hydrography component of the sustained ocean observing system for climate consists of a systematic re-occupation of select hydrographic sections to quantify global changes in storage and transport of heat, fresh water, carbon dioxide (CO₂), chlorofluorocarbon tracers and related parameters.



The program builds upon earlier programs (e.g., World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Survey (JGOFS) during the 1990s) that

have shown where atmospheric constituents are stored in the oceans and have provided full depth data sets against which to measure future changes (Sabine et al., 2004). This program should reveal much about internal transport pathways and changing patterns that may impact the carbon distributions and sinks on decadal time scales. It is also designed to assess changes in the ocean's biogeochemical cycle in response to natural and/or man-induced activity. For instance, global warming-induced changes in the ocean's transport of heat and freshwater, which could affect the circulation by decreasing or shutting down the thermohaline overturning, can be followed through long-term measurements. The program will also provide reference data for the Argo sensor calibration (e.g., www.argo.ucsd.edu), and support for continuing model development that will lead to improved forecasting skill for oceans and global climate.

Studies over the last two decades have increased our understanding of many aspects of carbon cycle in the oceans, but it is still uncertain how to interpret the sum of these studies for all of the oceans. For example, Bates et al. (2002) suggested that a lack of strong wintertime mixing in the subtropical mode waters of the North Atlantic during the positive phase of the North Atlantic Oscillation (NAO) may help to explain why subsurface DIC concentrations have been increasing almost twice as fast in the early 1990s as surface concentrations near Bermuda. Moreover, Gruber et al. (2002) conducted modeling studies that indicated that the NAO could account for an inter-annual variability of about $\pm 0.3 \text{ Pg C yr}^{-1}$ in the North Atlantic carbon sink. Similarly, Emerson et al., (2001) and Ono (2001) reported on increases in apparent oxygen utilization (AOU) in the upper thermocline of the eastern and western North Pacific Ocean, respectively, which they attributed to recent changes in circulation. However, the following year Keller et al., (2002) examined a larger area and also found AOU changes, but suggested that compensating changes in the opposite direction may be found deeper in the water column. These studies examined different regions, depth zones and time periods using differing approaches making it difficult to assess if the signals were coherent across the entire basin. Although the list of local and regional variations is growing quickly, comprehensive basin wide water column studies of decadal changes are needed to develop global scale appreciation of the changes and to assess the large-scale feedbacks between the ocean carbon cycle and climate.

The U.S. CLIVAR/ CO_2 Repeat Hydrography Program started in 2003 with the reoccupation of three WOCE Sections in the North Atlantic: A16N, A20, and A22 (Figure 1). This program is the United States contribution to the global biogeochemical and hydrographic resurvey under auspices of the CLIVAR program. A16N is a meridional section nominally along 20°W in the eastern basin of the North Atlantic that was last occupied by U. S. investigators in 1993. The NOAA Ship *Ronald H. Brown* departed from Iceland in June of 2003 conducting full water column measurements to 6°S . The other two sections were conducted on the *R/V Knorr* from Woods Hole, MA between September and November of 2003. The first leg (A20) was along 52°W and ended in Trinidad; the second leg (A22) was along 66°W and ended back in Woods Hole (Figure 1). In addition to the dissolved inorganic carbon (DIC) measurements, samples also were analyzed on board ship for salinity, dissolved oxygen, nutrients, titration alkalinity (TA), and chlorofluorocarbons (CFCs). Water samples were collected for

shore-based analyses of helium, tritium, dissolved organic carbon, ^{13}C , ^{14}C , and trace metals.

The analysis of the A16N cruise data show that between the 2003 section and earlier occupations in 1988, 1993 and 1998, significant long-term changes in water mass properties have occurred. These changes include increases in temperature and salinity, decreases in dissolved oxygen, and increases in dissolved inorganic carbon observed just below the Subpolar Mode Water (north of 35°N below 500 m).

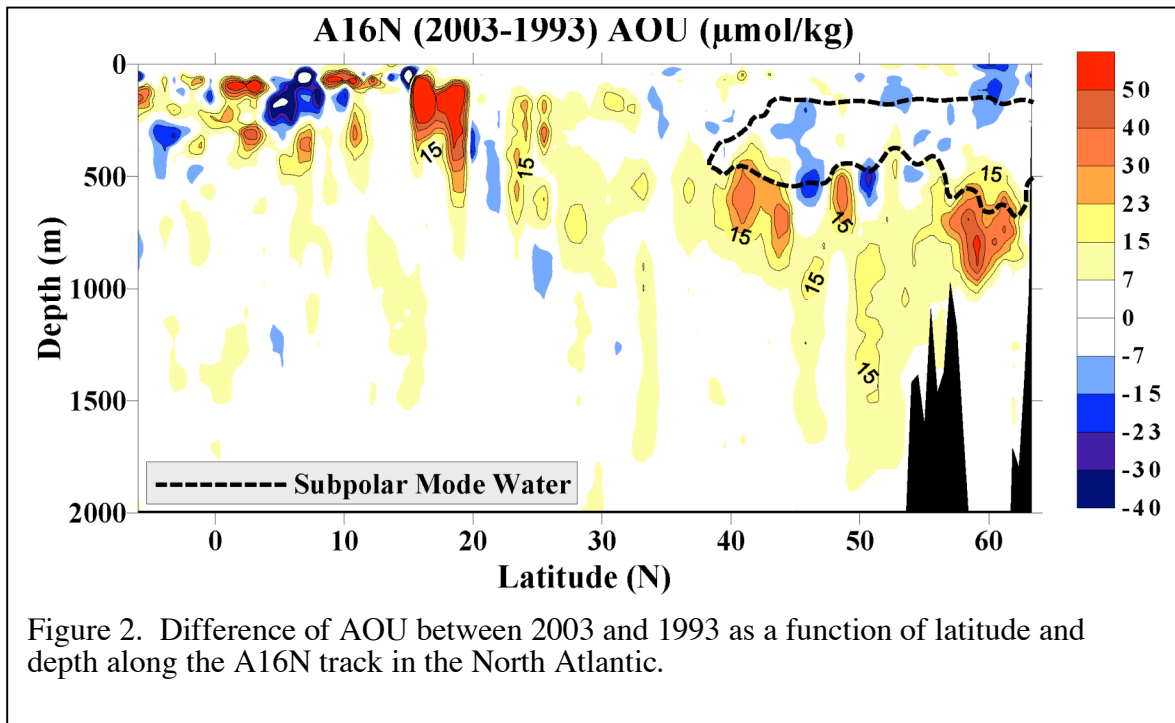


Figure 2. Difference of AOU between 2003 and 1993 as a function of latitude and depth along the A16N track in the North Atlantic.

The increase in apparent oxygen utilization (AOU), ranging from 5 - 50 $\mu\text{mol kg}^{-1}$ observed in the subpolar region of the North Atlantic (Figure 2) appears to be due to changes in the regional circulation and ventilation processes in the region during the decade prior to the 2003 occupation compared to the years prior to the earlier samplings (Johnson and Gruber, submitted). Changes in biological production, organic matter export, and remineralization rates may also play a role. Regions in the water column with large increases in AOU tended to have increases in pCFC ages, indicating that the AOU changes may be driven by circulation or ventilation changes after the 1995-96 NAO negative shift .

The data also indicate significant increases of DIC in the uppermost surface waters (0-500m) and near the base of the Subpolar Mode Water (Figure 3). The surface water increases (5-30 $\mu\text{mol kg}^{-1}$) are primarily due to the uptake of anthropogenic CO_2 from the atmosphere. The deepwater increases of about 10-20 $\mu\text{mol kg}^{-1}$ found just below the Subpolar Mode Water at about 600-1000m are highly correlated with the AOU increases, indicating that these DIC increases are most likely due to changes in regional

circulation, remineralization and ventilation. In contrast, the DIC at depths >1500m showed very little change (Wanninkhof et al., 2004).

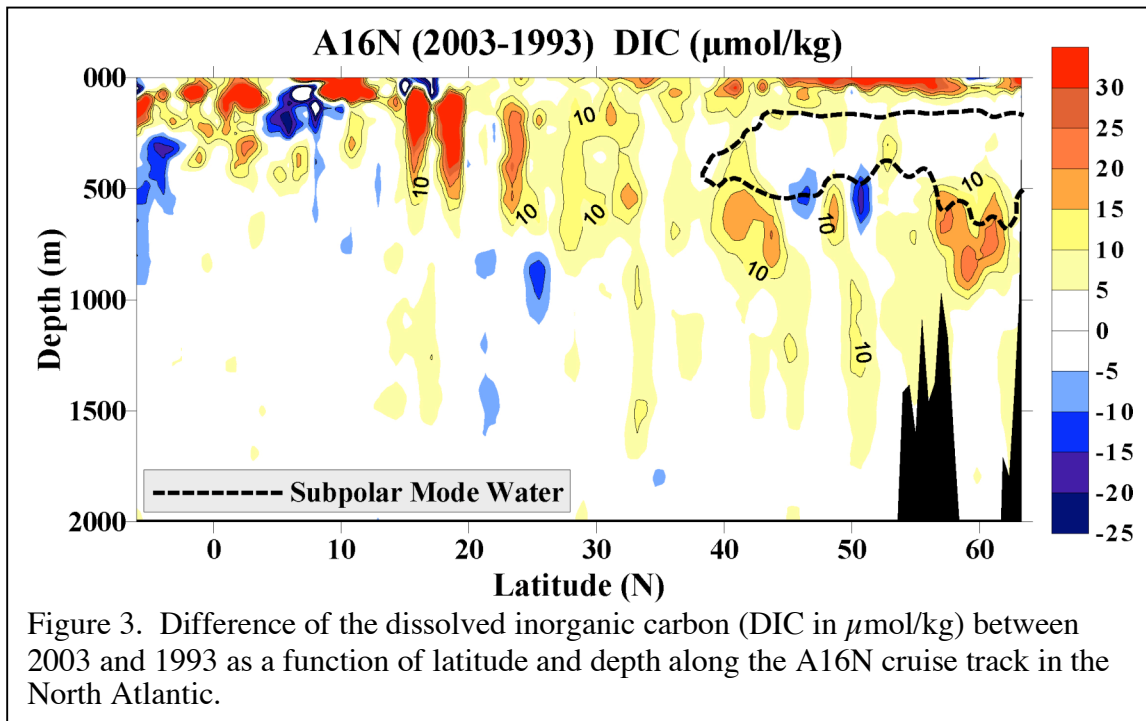


Figure 3. Difference of the dissolved inorganic carbon (DIC in $\mu\text{mol/kg}$) between 2003 and 1993 as a function of latitude and depth along the A16N cruise track in the North Atlantic.

Similar changes in DIC and AOU were also observed between 0-1200m for the A22/A20 cruises in the western North Atlantic. The increases of DIC in the Subtropical Mode Water (STMW) there are greater than expected from invasion of anthropogenic CO_2 from the atmosphere and may also be the result of decadal changes in the local circulation and ventilation processes in the North Atlantic, and/or changes in new production and remineralization of organic matter along the flow path. Our preliminary estimates indicate a mean CO_2 uptake rate of approximately $0.7 \pm 0.2 \text{ moles m}^{-2} \text{ yr}^{-1}$ for the North Atlantic during the past decade, somewhat lower than what has been observed in the North Pacific (Peng et al., 2003, Sabine et al., 2004). This preliminary result was unexpected because Sabine et al (2004) have shown that, over the course of the industrial era, the North Atlantic has taken up more than 3 times the amount of anthropogenic CO_2 per unit area than the North Pacific. This surprising result may be related to the 1995/1996 phase shift from high NAO to lower NAO. As U.S and international investigators collaborate on combining and analyzing data sets, we should be able to better determine the spatial variability of the carbon and oxygen distributions in the Atlantic Ocean and how they are affected by decadal changes in circulation and ventilation processes.

These cruises also provided the first ever high-resolution basin scale sections of dissolved organic carbon (DOC) and dissolved Fe in the North Atlantic. The new data revealed information on the export of DOC with the formation of North Atlantic Deep Water. In waters deeper than 2000m DOC concentrations ranged from $48 \mu\text{M}$ in waters characteristic of NADW and as low as $39 \mu\text{M}$ in waters characteristic of AABW

(Goldberg et al., 2004). The dissolved Fe data showed enrichments in the water masses directly underneath the Saharan dust input region west of Africa, which apparently are the result of soluble aerosol Fe loading, biological uptake, and intense Fe regeneration (Landing et al., 2004). These highly-resolved data sets are already changing our understanding of carbon cycle processes in the Atlantic and will be used to assess temporal as well as spatial trends of these important parameters.

The U.S. CLIVAR/CO₂ Repeat Hydrography Program is jointly sponsored by the National Science Foundation's Physical and Chemical Oceanography Programs and NOAA's Office of Climate Observation, with contributions from the National Aeronautics and Space Administration and the Department of Energy. We are currently seeking junior level scientists (postdocs, assistant level scientists) for participation as co-chief scientists and graduate students for general participation during upcoming cruises to the Pacific and Indian Oceans. For more information, please go to the CLIVAR/CO₂ Repeat Hydrography Program website at: <http://ushydro.ucsd.edu/index.html>

- Richard A. Feely, NOAA Pacific Marine Environmental Laboratory, Seattle, WA 98115 (e-mail: Richard.A.Feely@noaa.gov).
- Lynne D. Talley, Scripps Institution of Oceanography, La Jolla, CA 92093 (e-mail: ltalley@ucsd.edu).
- Gregory C. Johnson, NOAA Pacific Marine Environmental Laboratory, Seattle, WA 98115 (e-mail: Gregory.C.Johnson@noaa.gov).
- Christopher L. Sabine, NOAA Pacific Marine Environmental Laboratory, Seattle, WA 98115 (e-mail: Chris.Sabine@noaa.gov).
- Rik Wanninkhof, NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL 33149, (e-mail: Rik.Wanninkhof@noaa.gov).

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